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THE $\eta(1405)$, $\eta(1475)$, $f_1(1420)$, AND $f_1(1510)$

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The first observation of the $\eta(1440)$ was made in $p\overline{p}$ annihilation at rest into $\eta(1440)\pi^+\pi^-$, $\eta(1440) \to K\overline{K}\pi$ [1]. This state was reported to decay through $a_0(980)\pi$ and $K^*(892)\overline{K}$ with roughly equal contributions. The $\eta(1440)$ was also observed in radiative $J/\psi(1S)$ decay into $K\overline{K}\pi$ [2–4] and $\gamma\rho$ [5]. There is now evidence for the existence of two pseudoscalars in this mass region, the $\eta(1405)$ and $\eta(1475)$. The former decays mainly through $a_0(980)\pi$ (or direct $K\overline{K}\pi$) and the latter mainly to $K^*(892)\overline{K}$.

The simultaneous observation of two pseudoscalars is reported in three production mechanisms: π^-p [6,7]; radiative $J/\psi(1S)$ decay [8,9]; and $\overline{p}p$ annihilation at rest [11–14]. All of them give values for the masses, widths, and decay modes in reasonable agreement. However, Ref. [9] favors a state decaying into $K^*(892)\overline{K}$ at a lower mass than the state decaying into $a_0(980)\pi$, although agreement with MARK-III is not excluded. In $J/\psi(1S)$ radiative decay, the $\eta(1405)$ decays into $K\overline{K}\pi$ through $a_0(980)\pi$, and hence a signal is also expected in the $\eta\pi\pi$ mass spectrum. This was indeed observed by MARK III in $\eta\pi^+\pi^-$ [15], which reports a mass of 1400 MeV, in line with the existence of the $\eta(1405)$ decaying into $a_0(980)\pi$. BES [10] reports an enhancement in $K^+K^-\pi^0$ around 1.44 GeV in $J/\psi(1S)$ decay, recoiling against an ω (but not a ϕ) without resolving the presence of two states nor performing a spin-parity analysis, due to low statistics. This state could also be the $f_1(1420)$ (see below).

The $\eta(1405)$ is also observed in $\overline{p}p$ annihilation at rest into $\eta\pi^+\pi^-\pi^0\pi^0$, where it decays into $\eta\pi\pi$ [16]. The intermediate $a_0(980)\pi$ accounts for roughly half of the $\eta\pi\pi$ signal, in agreement with MARK III [15] and DM2 [4].

The $\eta(1295)$ has been observed by four π^-p experiments [7,17–19], and evidence is reported in $\overline{p}p$ annihilation [23–25]. In $J/\psi(1S)$ radiative decay, an $\eta(1295)$ signal is evident in the 0^{-+} $\eta\pi\pi$ wave of the DM2 data [9]. Also BaBar [20] reports evidence for a signal around 1295 MeV in B decays into $\eta\pi\pi K$.

However, the existence of the $\eta(1295)$ is questioned in Refs. [21] and [22]. The authors claim a single pseudoscalar meson in the 1400 MeV region. This conclusion is based on properties of the wave functions in the $^3P_0$ model (and on an unpublished analysis of the annihilation $\bar{p}p \to 4\pi\eta$). The pseudoscalar signal around 1400 MeV is then attributed to the first radial excitation of the η.

Assuming establishment of the $\eta(1295)$, the $\eta(1475)$ could be the first radial excitation of the η', with the $\eta(1295)$ being the first radial excitation of the η. Ideal mixing, suggested by the $\eta(1295)$ and $\pi(1300)$ mass degeneracy, would then imply that the second isoscalar in the nonet is mainly $s\bar{s}$, and hence couples to $K^*\overline{K}$, in agreement with properties of the $\eta(1475)$. Also, its width matches the expected width for the radially excited $s\bar{s}$ state [26,27]. A study of radial excitations of pseudoscalar mesons [28] favors the $s\bar{s}$ interpretation of the $\eta(1475)$. However, due to the strong kinematical suppression the data are not sufficient to exclude a sizeable $s\bar{s}$ admixture also in the $\eta(1405)$.

The $K\overline{K}\pi$ and $\eta\pi\pi$ channels were studied in $\gamma\gamma$ collisions by L3 [29]. The analysis leads to a clear $\eta(1475)$ signal in $K\overline{K}\pi$, decaying into $K^*\overline{K}$, very well identified in the untagged data sample, where contamination from spin 1 resonances is not allowed. At the same time, L3 [29] did not observe the $\eta(1405)$, neither in $K\overline{K}\pi$ nor in $\eta\pi\pi$. The observation of the $\eta(1475)$, combined with the absence of an $\eta(1405)$ signal, strengthens the two-resonances hypothesis. Since gluonium production is presumably suppressed in $\gamma\gamma$ collisions, the L3 results [29] suggest that $\eta(1405)$ has a large gluonic content (see also Refs. [30] and [31]) .

The L3 result is somewhat in disagreement with that of CLEO-II, which did not observe any pseudoscalar signal in $\gamma\gamma \to \eta(1475) \to K^0_S K^\pm \pi^\mp$ [32]. However, more data are required. Moreover, after the CLEO-II result, L3 performed a further analysis with full statistics [33], confirming the evidence of the $\eta(1475)$ observed by L3. The CLEO upper limit [32] for $\Gamma_{\gamma\gamma}(\eta(1475))$, and the L3 results [33], are consistent with the world average for the $\eta(1475)$ width.

BaBar [20] also reports the $\eta(1475)$ in B decays into $K\bar{K}\pi$ (and possibly $\eta\pi\pi$). Upper limits are given for $\eta(1405)$ decay into $K\bar{K}^*$. The data sample is not sufficient to identify a possible $\eta(1405)$ contribution into $\eta\pi\pi$.

The gluonium interpretation for the $\eta(1405)$ is not favored by lattice gauge theories which predict the 0^{-+} state above 2 GeV [34]. However, the $\eta(1405)$ is an excellent candidate for the 0^{-+} glueball in the fluxtube model [35]. In this model, the 0^{++} $f_0(1500)$ glueball is also naturally related to a 0^{-+} glueball with mass degeneracy broken in QCD. Also, Ref. [36] shows that the pseudoscalar glueball could lie at a lower mass than predicted from lattice calculation. In this model the $\eta(1405)$ appears as the natural glueball candidate (see also Refs. [37] and [38]) . A detailed review of the experimental situation is available in Ref. [39].

Let us now deal with 1^{++} isoscalars. The $f_1(1420)$, decaying into $K^*\overline{K}$, was first reported in $\pi^- p$ reactions at 4 GeV/c [40]. However, later analyses found that the 1400–1500 MeV region was far more complex [41–43]. A reanalysis of the MARK III data in radiative $J/\psi(1S)$ decay into $K\overline{K}\pi$ [8] shows the $f_1(1420)$ decaying into $K^*\overline{K}$. Also, a C=+1 state is observed in tagged $\gamma\gamma$ collisions (*e.g.*, Ref. [44]) .

In $\pi^- p \to \eta\pi\pi n$ charge-exchange reactions at 8–9 GeV/c the $\eta\pi\pi$ mass spectrum is dominated by the $\eta(1440)$ and $\eta(1295)$ [17,45], and at 100 GeV/c Ref. [18] reports the $\eta(1295)$ and $\eta(1440)$ decaying into $\eta\pi^0\pi^0$ with a weak $f_1(1285)$ signal, and no evidence for the $f_1(1420)$.

Axial (1^{++}) mesons are not observed in $\overline{p}p$ annihilation at rest in liquid hydrogen, which proceeds dominantly through S-wave annihilation. However, in gaseous hydrogen, P-wave annihilation is enhanced and, indeed, Ref. [12] reports $f_1(1420)$ decaying into $K^*\overline{K}$. The $f_1(1420)$, decaying into $K\overline{K}\pi$, is also seen in pp central production, together with the $f_1(1285)$. The latter decays via $a_0(980)\pi$, and the former only via $K^*\overline{K}$, while the $\eta(1440)$ is absent [46,47]. The $K_S K_S \pi^0$ decay mode of the $f_1(1420)$ establishes unambiguously C=+1. On the other hand, there is no evidence for any state decaying into $\eta\pi\pi$ around

1400 MeV, and hence the $\eta\pi\pi$ mode of the $f_1(1420)$ must be suppressed [48].

We now turn to the experimental evidence for the $f_1(1510)$. Two states, the $f_1(1420)$ and $f_1(1510)$, decaying into $K^*\overline{K}$, compete for the $s\overline{s}$ assignment in the 1^{++} nonet. The $f_1(1510)$ was seen in $K^-p \rightarrow \Lambda K\overline{K}\pi$ at 4 GeV/c [49], and at 11 GeV/c [50]. Evidence is also reported in π^-p at 8 GeV/c, based on the phase motion of the 1^{++} $K^*\overline{K}$ wave [43]. A somewhat broader 1^{++} signal is also observed in $J/\psi(1S)$ radiative decay into $\eta\pi^+\pi^-$ [51].

The absence of $f_1(1420)$ in K^-p [50] argues against the $f_1(1420)$ being the $s\overline{s}$ member of the 1^{++} nonet. However, the $f_1(1420)$ was reported in K^-p but not in π^-p [52], while two experiments do not observe the $f_1(1510)$ in K^-p [52,53]. The latter is also not seen in radiative $J/\psi(1S)$ decay [8,9] and possibly [10], central collisions [47], or $\gamma\gamma$ collisions [54], although, surprisingly for an $s\overline{s}$ state, a signal is reported in 4π decays [55]. These facts lead to the conclusion that $f_1(1510)$ is not well established [56].

Assigning the $f_1(1420)$ to the 1^{++} nonet, one finds a nonet mixing angle of $\sim 50°$ [56]. However, arguments favoring the $f_1(1420)$ being a hybrid $q\overline{q}g$ meson, or a four-quark state, were put forward in Refs. [57] and [58], respectively, while Ref. [59] argued for a molecular state formed by the π orbiting in a P-wave around an S-wave $K\overline{K}$ state.

Summarizing, there is convincing evidence for the $f_1(1420)$ decaying into $K^*\overline{K}$, and for two pseudoscalars in the $\eta(1440)$ region, the $\eta(1405)$ and $\eta(1475)$, decaying into $a_0(980)\pi$ and $K^*\overline{K}$, respectively. The $f_1(1510)$ is not well established.

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